

## Procidia Control Solutions Cascade Control

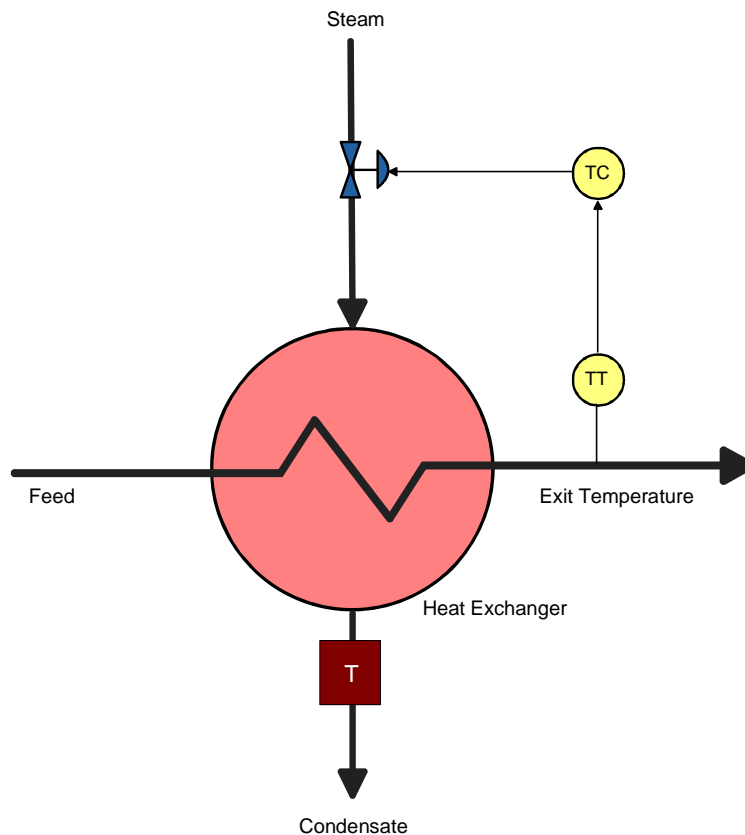
This application data sheet describes cascade control techniques. A cascade control configuration can be easily developed within a Siemens 353 controller.<sup>1</sup>

Cascade control uses a secondary controller in conjunction with a primary controller to improve control of the primary process variable. In cascade control, the output of a primary controller manipulates the setpoint of a secondary controller. This control strategy increases the speed of the primary control loop and is particularly useful for minimizing the effect of load changes that disturb the primary variable.

### SINGLE-LOOP CONTROL OF HEAT EXCHANGER

Figure 1 shows an example in which cascade control would be beneficial. In this heat exchanger example, exit temperature is the primary control variable. The temperature controller (TC) manipulates the flow of steam to the heat exchanger to control the exit temperature at setpoint.

An increase in the feed flow to the heat exchanger will cause a decrease in the exit temperature. The temperature controller responds to this control error



**Figure 1 Heat Exchanger Temperature Control**

<sup>1</sup> See Applications Support at the back of this publication for a list of controllers.

by increasing the steam flow as required to return the exit temperature to the setpoint. The change in feed flow represents a change in load on the heat exchanger and is referred to as a load disturbance. Other load disturbances that can affect the exit temperature are changes in feed temperature, ambient temperature, and steam pressure.

To apply cascade control to the heat exchanger, an appropriate secondary variable needs to be selected. The secondary variable must be one that can be measured and controlled as a dependent variable of the primary control loop, and it must have a direct effect on the primary process variable. The secondary control loop should encompass at least one of the load variables affecting the primary variable, and it should respond considerably faster than the primary loop.

The most common variable used for secondary control is the manipulated variable already being used by the single loop controller. In the heat exchanger example, steam flow is the manipulated variable. As shown in Figure 2, an increase in steam pressure causes an increase in steam flow. The increase in steam flow will eventually cause an increase in outlet temperature that must be corrected by the temperature controller. As the controller throttles the steam valve to compensate for the increase in steam pressure, the steam flow is returned to its original value as the temperature is returned to setpoint.

## CASCADE CONTROL OF HEAT EXCHANGER

Figure 3 shows a flow controller (FC) in cascade with the temperature controller (TC). The flow controller manipulates the valve to control the steam flow at a setpoint manipulated by the temperature controller. Since steam flow responds rapidly to changes in pressure and valve position, the flow controller can correct for a change in steam pressure before it has a chance to disturb the exit temperature. Figure 4 shows the same response as Figure 2 but with cascade control implemented. It shows the dramatic improvement that is possible when using cascade control to isolate the exit temperature from steam changes.

## ADVANTAGES OF CASCADE CONTROL

The heat exchanger example illustrates the four major advantages of cascade control: isolation of load disturbances, improved speed of response, precise manipulation of mass or energy, and compensation for nonlinearities.

### Load Disturbance Isolation

Cascade control can, to a large extent, isolate the primary variable from disturbances that enter the secondary control loop. The amount of isolation achieved depends on the relative speeds of the primary and secondary control loops. If the secondary loop is much faster than the primary loop,

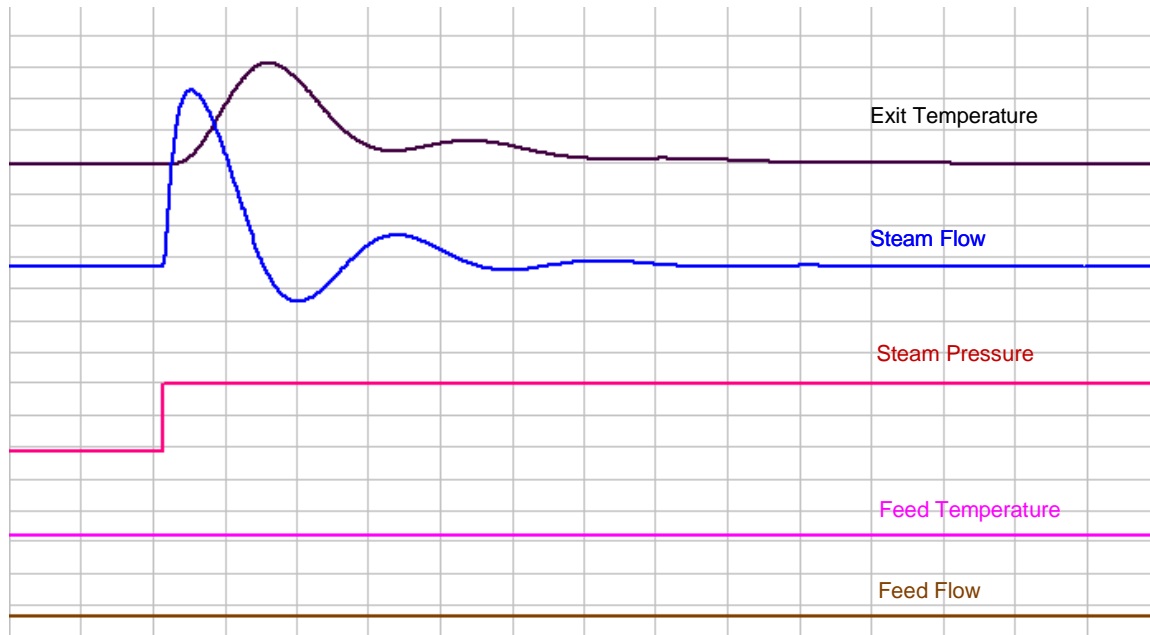


Figure 2 Single-Loop Response to Steam Pressure Change

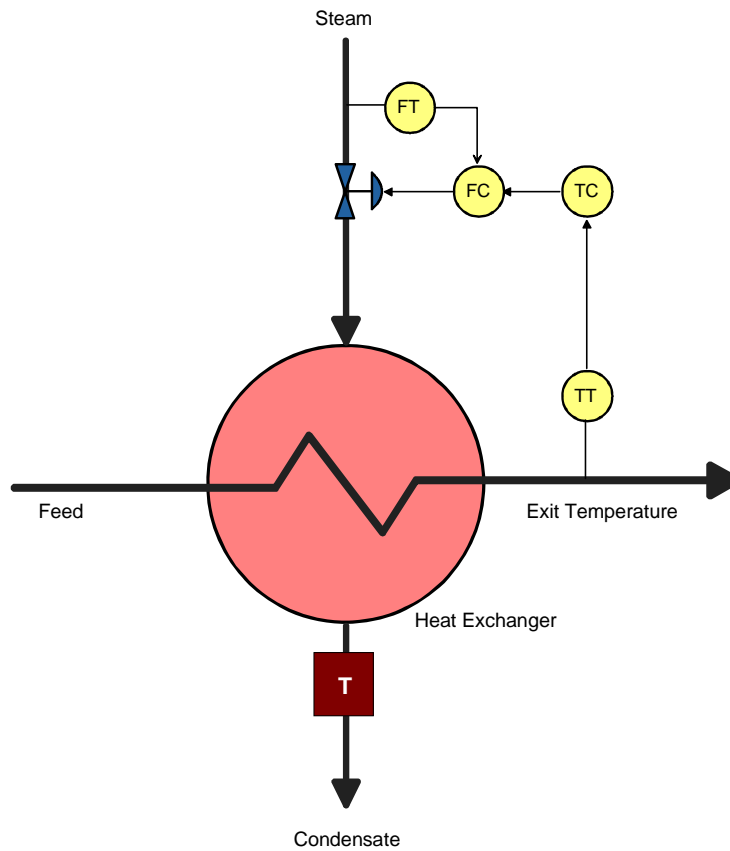


Figure 3 Heat Exchanger Cascade Control

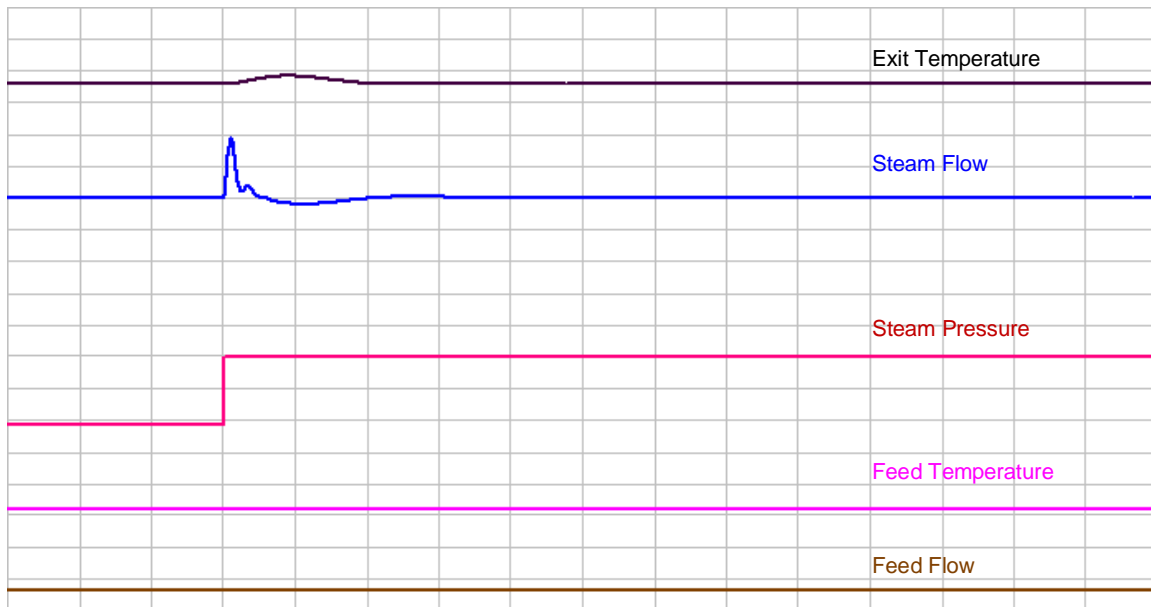


Figure 4 Cascade Response to Steam Pressure Change

the load disturbance can be corrected before the primary loop can respond. For good load disturbance isolation, the secondary loop should be about 10 times faster than the primary loop.

### Speed of Response Improvement

Cascade control cannot isolate the primary variable from disturbances that enter the primary loop outside of the secondary loop; for example, feed temperature and feed flow changes are disturbances that enter outside of the steam flow control loop. Cascade control can, in some cases, improve the speed at which the primary controller can compensate for these disturbances.

### Precise Manipulation of Mass or Energy

The use of a flow control loop in the manipulated variable provides precise delivery of mass or energy. Rather than depend on an open loop relationship between flow and valve position, the valve is manipulated by the controller until the required flow is achieved. For gas flow, the flow measurement can also be compensated for variations in line pressure and temperature to maintain accurate flow metering. See AD353-124 for information on pressure and temperature compensation of an orifice flowmeter.

### Compensation for Nonlinearities

Control valves have inherent flow characteristics such as linear, equal percentage, and quick opening. With the exception of the linear characteristic, all are inherently nonlinear. These characteristics are based on a constant differential pressure across the valve. In reality, however, control valves rarely operate with a constant differential; instead, the differential varies with the flow through the valve, which is often a function of the process load. The inherently nonlinear valve characteristics are intended to compensate for variations in differential pressure to achieve a linear installed characteristic. Due to misapplication of the valve characteristics and differential pressures that do not behave as expected, there often remains a nonlinear relationship between flow and valve position. A flow control loop provides compensation for these nonlinearities by positioning the valve as required to achieve the desired flow.

### Typical Secondary Variables

The most common secondary variable is valve position. Any control valve equipped with a valve positioner is actually a secondary control loop. The valve positioner is a high gain proportional-only controller that uses mechanical feedback from the

valve to sense its actual position. The valve positioner manipulates the air loading on the valve until the valve position matches that demanded by the controller.

The next most common secondary variable is flow. Since flow is the manipulated variable in the vast majority of control loops, flow is the obvious choice in many cascade control strategies. In the heat exchanger example, downstream (shell) pressure could also be used as a secondary variable.

Temperature is another common secondary variable. It is most often used on jacketed reactors. Temperature can also be used as a secondary variable in composition control loops on distillation columns.

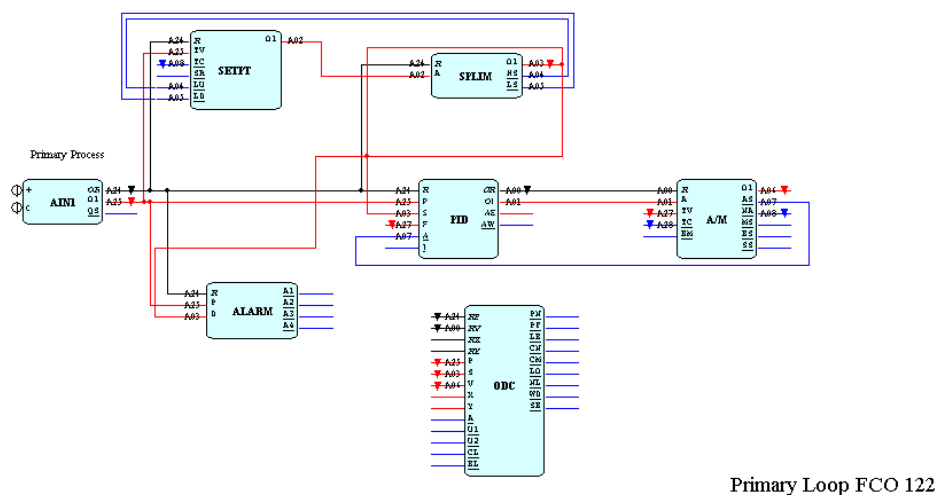
Cascade control can improve the performance of many control loops. The combination of cascade control and feedforward control offers even more potential for improvement. The balance of this publication describes techniques for implementing cascade and cascade plus feedforward control.

## CASCADE CONTROL CONFIGURATION

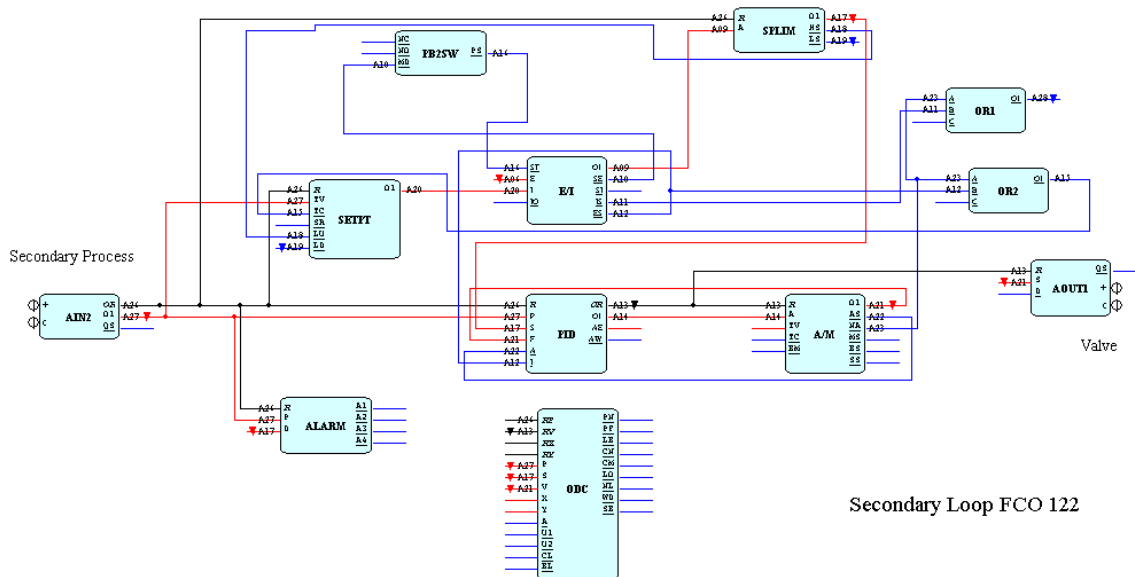
Two configurations for cascade control are already stored in the memory of a 353 controller as FCO (Factory Configuration Option) 121 and FCO122. FCO122 is identical to FCO121 except it includes operator limits on the primary and secondary controller setpoint. Figure 5 shows the configuration for the Primary loop of FCO122 and Figure 6 the configuration for the Secondary loop.

The primary PID controller manipulates the setpoint of the secondary PID controller to control the exit temperature at setpoint. The secondary PID controller manipulates the steam valve to control the steam flow at a value set by the primary controller. The SPLIM function block in the secondary loop clamps the output of the primary controller between adjustable limits. This prevents the primary controller from driving the secondary setpoint beyond the desired operating range. This feature might be more important in a cascade loop where the secondary process is temperature, such as a jacketed reactor.

The E/I transfer switch in the secondary loop allows the operator to select the source of the steam flow setpoint. In External, the secondary setpoint is provided by the PID controller in the primary loop. In Internal, the secondary setpoint is adjusted by the operator for secondary automatic control. This operating mode is useful for startup and tuning the secondary control loop.



**Figure 5 Cascade Controller – Primary Loop (FCO122)**



**Figure 6 Cascade Controller – Secondary Loop, FCO122**

The A/M transfer switch in the primary loop is required for the auto tune algorithm to function. The A/M block may be switched to manual to bring the process to a steady state condition prior to starting the auto tuner. This block would not normally be used by an operator and could be configured for auto only by setting the "A ONLY" parameter to "YES" after initial setup has been completed.

The A/M transfer switch in the secondary loop allows the operator to switch between auto and manual modes of operation. In Auto, the secondary controller manipulates the steam valve. In Manual, the steam valve position is adjusted by the operator.

When control is switched to Manual or External, OR logic forces the SETPT block in the secondary loop to the track process variable. This aligns the setpoint with the steam flow for bumpless transfer to secondary auto mode.

When control is switched to Manual or Internal, OR logic forces the SETPT block in the primary loop to track the primary process variable, and the SETPT block in the secondary loop to track the secondary process variable. This aligns the exit temperature setpoint and the steam flow setpoint for bumpless transfer to cascade control.

### Setpoint Tracking

Although FCO121 and FCO122 configure both setpoint blocks for setpoint tracking, it is not absolutely necessary to do so for bumpless transfer between modes. Without setpoint tracking, a control error may exist on the return to automatic control. To prevent a proportional bump, the PID blocks are initialized whenever the E/I or A/M switches are changed. Although the proportional bump is eliminated, integral action begins immediately to drive the process variable back to setpoint.

In the case of the secondary setpoint, tracking is preferred because there is generally no need to retain an independent setpoint. By definition, the secondary setpoint of a cascade loop depends on the needs of the primary process variable.

In the case of the primary setpoint, tracking depends on the user's preference. In general, the primary setpoint is an independent setting that may remain at the same value for extended periods of time. In this case, it may be preferable to use a non-tracking setpoint. This can be accomplished by eliminating the TC input of the SETPT function block.

### Secondary Variable Feedback

A key design feature is the use of the secondary process variable as reset feedback (input F) to the primary PID controller. This arrangement sets the pace for the primary loop relative to the secondary loop and prevents reset windup in the primary controller. It also aligns the primary controller for bumpless transfer to cascade control from secondary auto and manual modes of operation.

Both PID function blocks are reset feedback type controllers. With this type of controller, integral action is driven by reset feedback. For proper operation, the reset feedback signal must be either the output of the PID algorithm or an equivalent signal that represents the output. This signal provides positive feedback to the control algorithm through a first order lag. As long as a control error persists, this positive feedback loop drives the PID output at a rate determined by the lag time constant ( $\tau_i$ ) to provide integral action.

If the output of the PID block is used directly for reset feedback, any interruption in the path between the PID output and its manipulated variable can cause reset windup. In the case of the primary controller in this cascade configuration, the path can be interrupted by the output limits, the E/I transfer switch, the secondary controller, or the A/M transfer switch. Interruptions are also possible in the process, such as a sticking valve or loss of steam pressure. Any one of these interruptions can prevent the primary controller from manipulating the secondary variable to drive the primary process to setpoint. This results in a sustained control error that cannot be corrected by the primary controller. However, with secondary variable feedback, an interruption in the control loop also interrupts the positive feedback loop to halt integral action. This prevents reset windup and allows the controller to resume from the present value of the secondary variable when the interruption is eliminated.

Secondary variable feedback also guards against setting the integral action too fast in the primary controller. There is no reason for the primary controller to integrate faster than the secondary loop can respond. If the primary controller "gets ahead" of the secondary process, it can return to the appropriate value only by integrating a control error in the opposite direction. With secondary variable feedback, however, it is not possible for the primary controller to integrate any faster than the secondary loop can respond no matter what the integral setting.

## Tuning

In cascade control loops, the secondary controller must be tuned first. Tuning the secondary controller establishes the dynamics of the secondary loop, which is then one of the dynamic elements of the primary loop. The secondary loop must be in the External/Automatic mode while tuning the primary loop. More information on tuning can be found in AD353-119 which covers tuning methods of digital controllers and in the Autotune Procedure section of the 353 User Manual.

## CASCADE PLUS FEEDFORWARD CONTROL

Combining cascade and feedforward control techniques facilitates additional improvement in control loop performance. Figure 7 shows a heat exchanger control strategy that adds model predictive feedforward to cascade control.

Model predictive feedforward uses a rigorous mathematical model of the process to calculate the value of the manipulated variable as a function of one or more load variables. The primary feedback controller “trims” the model to compensate for modeling errors, or unmeasured load disturbances.

In cascade, the secondary controller provides precise delivery of the manipulated variable calculated by the feedforward model.

In the heat exchanger example, the mathematical model calculates the steam flow required to heat the feed flow from the feed temperature to the desired exit temperature. The steam flow controller delivers the steam required and compensates for disturbances in the steam supply. The exit temperature controller trims the mathematical model as required to control the outlet temperature at setpoint. Trimming the model has the effect of resetting the steam flow setpoint, as is the case with simple cascade control.

Figure 8 shows the response of the Cascade loop to changes in feed flow and feed temperature without feedforward. Figure 9 shows the response of a cascade plus feedforward loop to the same changes.

The configuration for cascade plus feedforward is shown in Figures 10 and 11. The configuration is FCO122 with added inputs for feed flow and feed temperature. Remote Ethernet I/O is used to bring in these variables. Math blocks are added to provide the feedforward compensation.

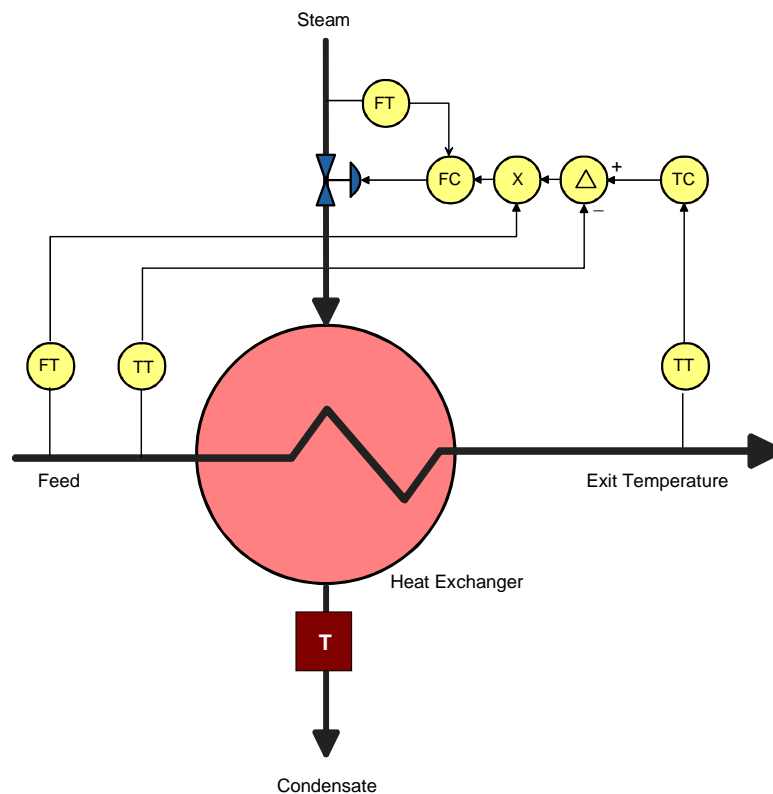


Figure 7 Cascade Plus Feedforward Control

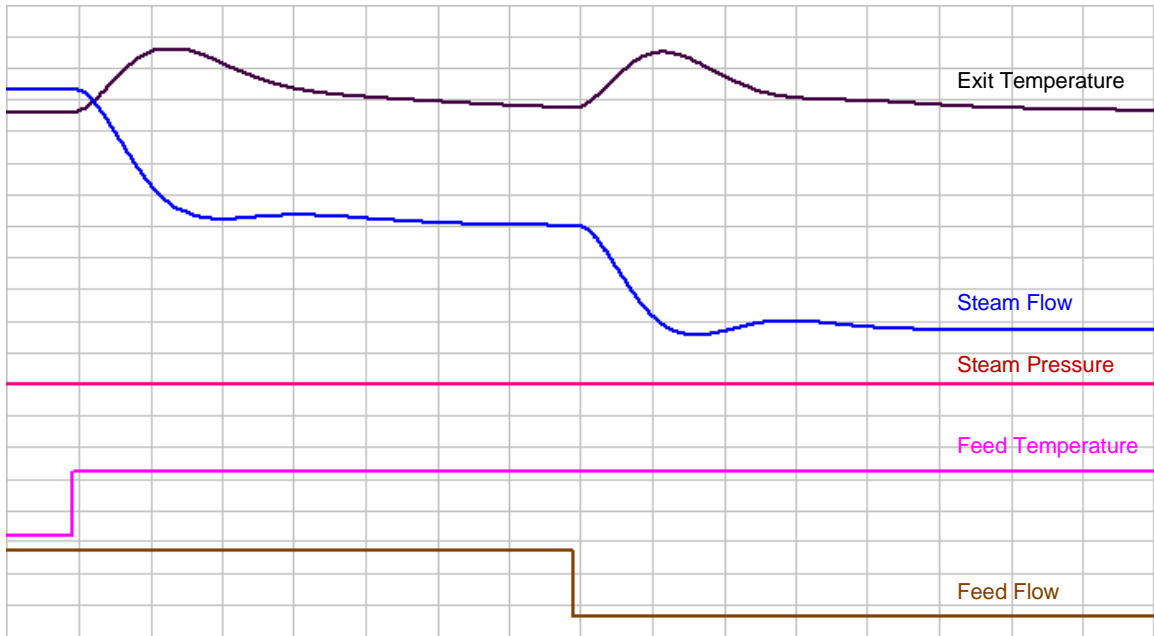


Figure 8 Cascade Response to Feed Flow and Temperature Changes

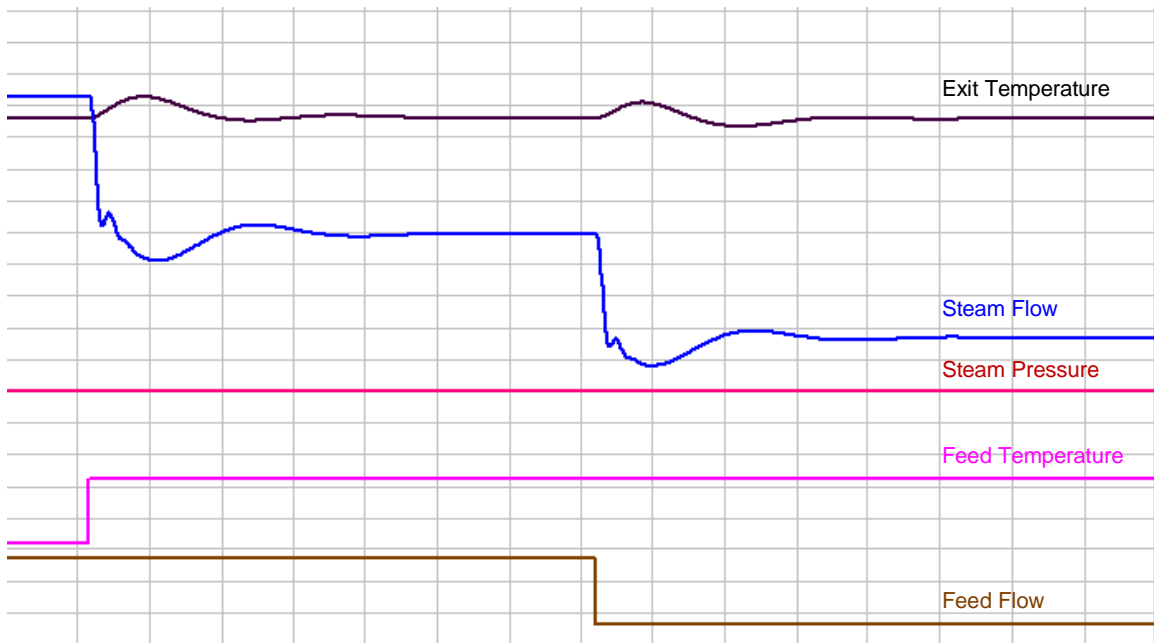


Figure 9 Cascade + Feedforward Response to Feed Flow and Temperature Changes



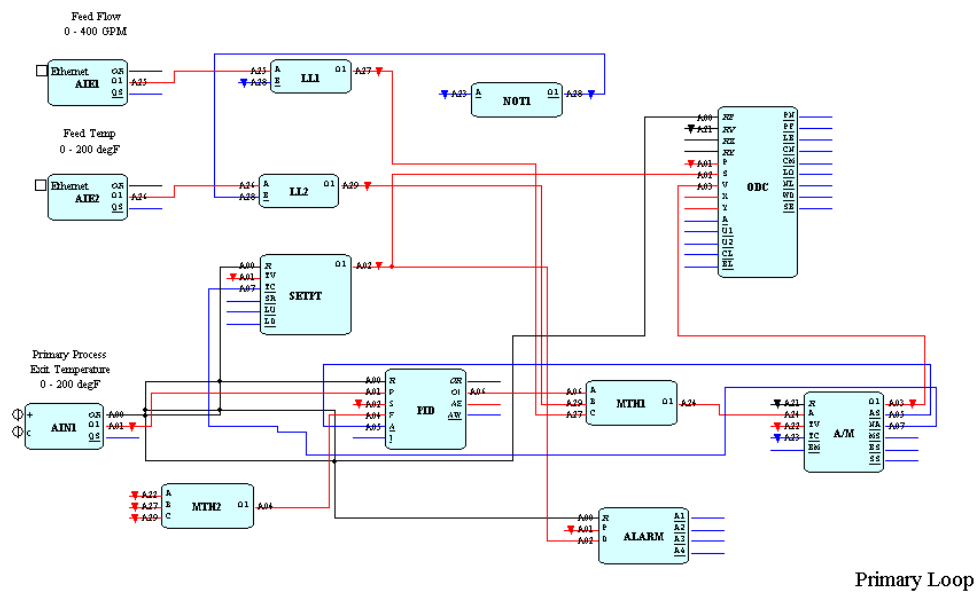


Figure 10 Primary Loop – Cascade + Feedforward (CF353-128PL)

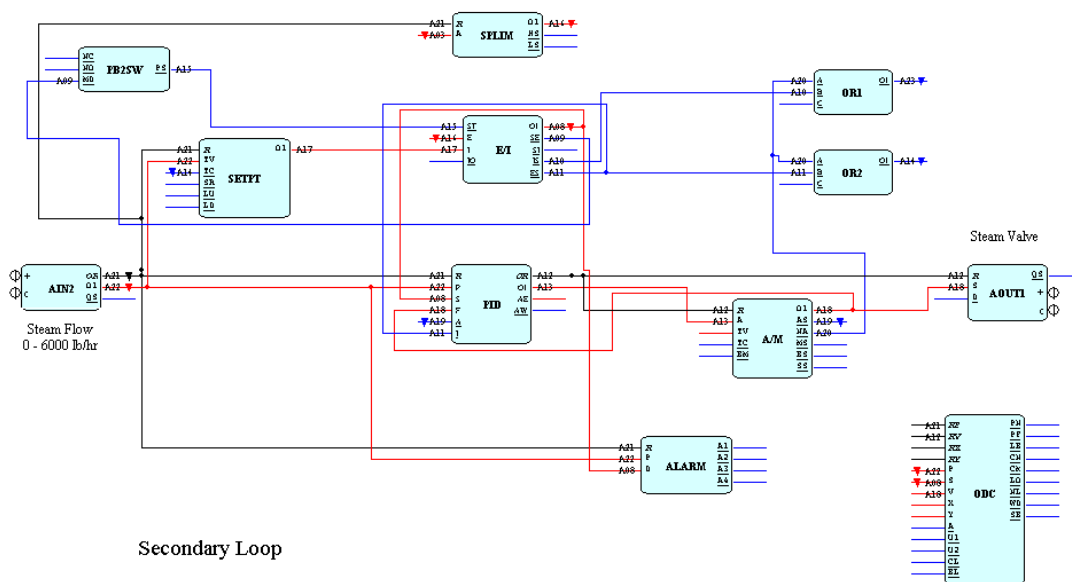


Figure 11 Secondary Loop – Cascade + Feedforward (CF353-128SL)

Math function block MTH1 is used to calculate the steam flow required as a function of the feed flow, feed temperature and exit temperature setpoint. Note that the output of the exit temperature controller is used instead of the exit temperature setpoint as a convenient method of providing feedback trim to the feedforward calculation. This requires that the output of the PID block be scaled in temperature units. In this configuration the output was scaled 0 – 200°F to match the range of the feed temperature input.

Lead Lag function blocks LL1 and LL2 provide dynamic lag compensation for the feedforward model. These blocks can provide both lead and lag compensation, if necessary, for the dynamic model.

Math function block MTH2 is used to calculate the appropriate reset feedback to the PID controller. Since the output of the primary controller represents temperature, the appropriate reset feedback is “back calculated” as a function of the steam flow, feed flow, and feed temperature. Additional information on the configuration of math blocks can be found in AD353-129 Feedforward Control.

By including the secondary variable in the feedback calculation, all the benefits of secondary variable feedback are retained. In Manual or Internal, the NOT1 logic block bypasses the lag blocks to avoid any delays in the feedforward and feedback calculations for switching purposes.

## APPLICATIONS

There are many additional applications for cascade control beyond the examples in this publication. Most involve flow loops as the secondary variable, such as reboiler temperature setting steam flow, and boiler drum level setting feedwater flow. The drum level application often includes feedforward from the steam

flow in the classic three-element drum level application.

Another common application uses temperature as the secondary variable. In jacketed reactors, the reactor temperature controller often sets the jacket temperature controller. Although jacket temperature response may be slow, it is generally faster than the reactor. The jacket temperature loop compensates for upsets in the supply of heating and cooling and improves the speed of reactor temperature control.

## APPLICATION SUPPORT

User manuals for controllers and transmitters, addresses of Siemens sales representatives, and more application data sheets can be found at [www.usa.siemens.com/ia](http://www.usa.siemens.com/ia). To reach the process controller page, click **Process Instrumentation** and then **Process Controllers and Recorders**. To select the type of assistance desired, click **Support** (in the right-hand column). See AD353-138 for a list of Application Data sheets.

The configuration(s) shown in this publication were created in Siemens *ilconfig*<sup>TM</sup> Graphical Configuration Utility. Those with CF353 in parenthesis in the Figure title are available using the above navigation, then click **Software Downloads > 353 Cascade Control (Reference AD353-128)**.

The configuration(s) can be created and run in a:

- Model 353 Process Automation Controller
- Model 353R Rack Mount Process Automation Controller\*
- *ilpac*<sup>TM</sup> Internet Control System\*
- Model 352*Plus*<sup>TM</sup> Single-Loop Digital Controller\*  
\* Discontinued model

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